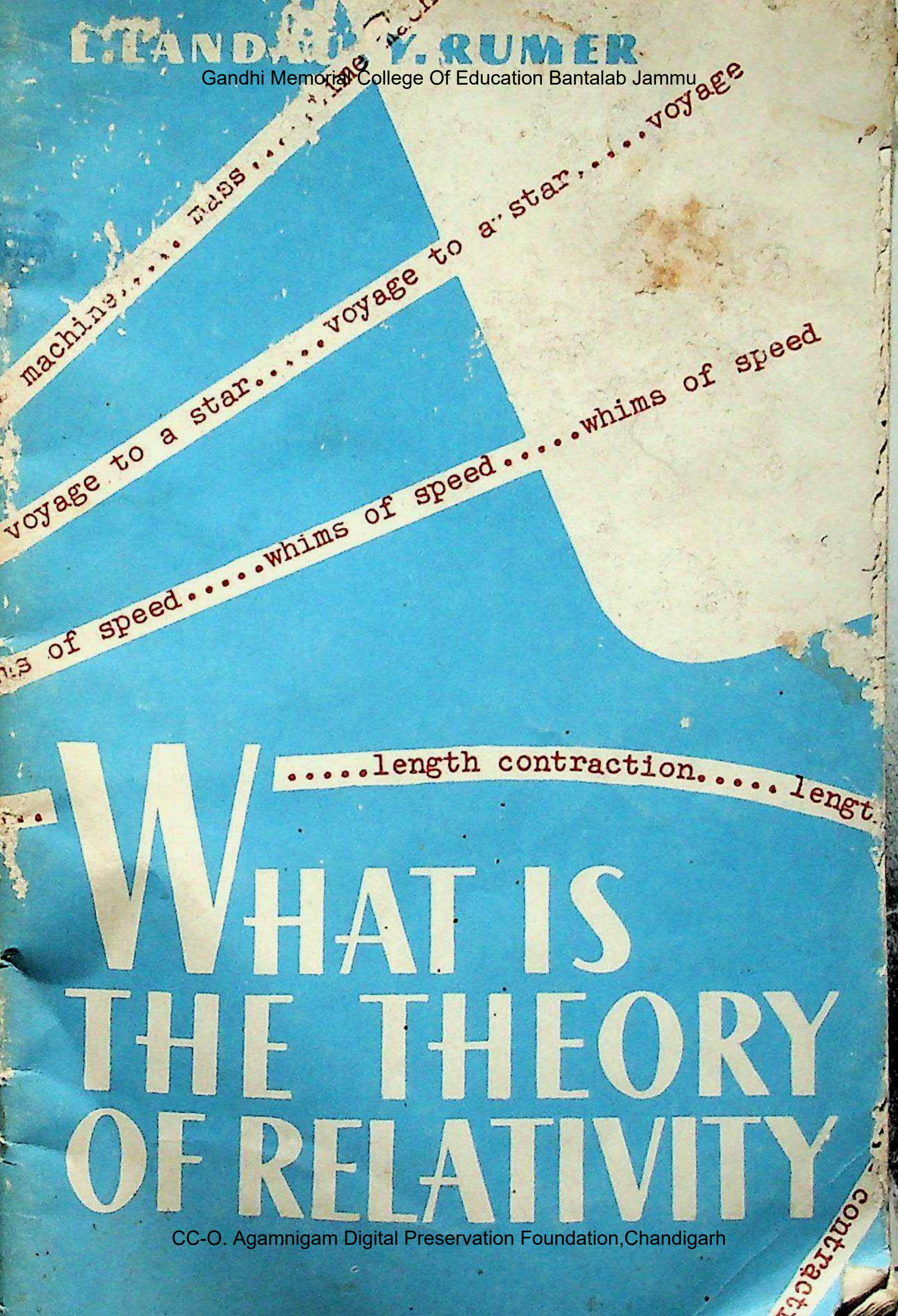
L. LANDAU Y. RUMER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WHAT IS THE THEORY OF RELATIVITY

ИЗДАТЕЛЬСТВО • МИР •

Л. Ландау, Ю. Румер

ЧТО ТАКОЕ ТЕОРИЯ ОТНОСИТЕЛЬНОСТИ

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WHAT IS THE THEORY OF RELATIVITY

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"...Undoubtedly mechanics was a 'snapshot' of slow and real motions, while new physics is a snapshot of fabulously swift and real motions. ...

The mutability of the human conceptions of space and time disproves the objective reality just as little as the mutability of our knowledge about the structure and forms of the motion of matter disproves the objective reality of the outside world."

V. I. LENIN

Chapter One

THE RELATIVITY WE ARE USED TO

Does Every Assertion Make Sense?

Obviously not. Even if we take some words and link them together in strict accordance with the rules of grammar, the result may be complete nonsense. There is no sense whatever, for example, in the assertion that "water is triangular".

However, not all nonsense is so obvious. All too often an assertion which appears quite reasonable at first glance turns out to be absolute nonsense under closer scrutiny.

Right or Left?

On what side of the street—right or left—is the house? You cannot possibly answer this question offhand.

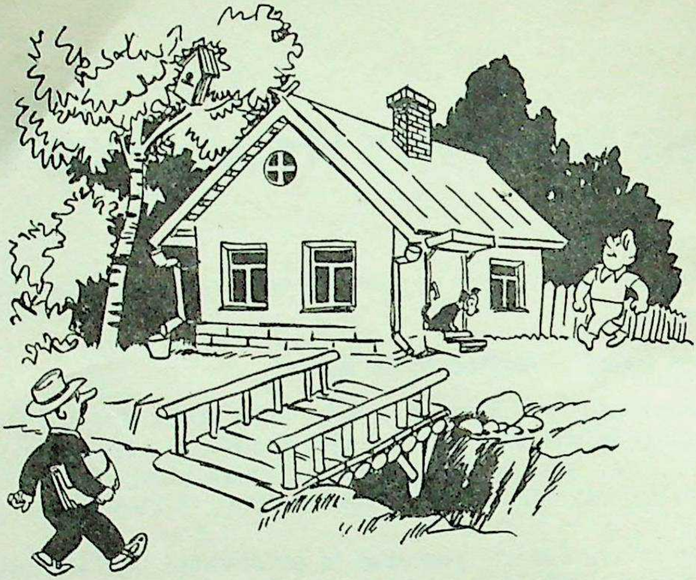
If you go from the bridge towards the wood, it will be on your left-hand side, and if you go in the opposite direction, it will be on your right. Speaking of the left- or right-hand side of a street you must mention the relative direction.

There is sense in speaking of the right bank of a river, because its current determines the direction. We can similarly say that a motor car drives along the right-hand side of the roadway, because the flow of traffic indicates the relative direction.

The notions "right" and "left" are therefore relative and make sense only when a direction is given to guide us.

Is It Day or Night Now?

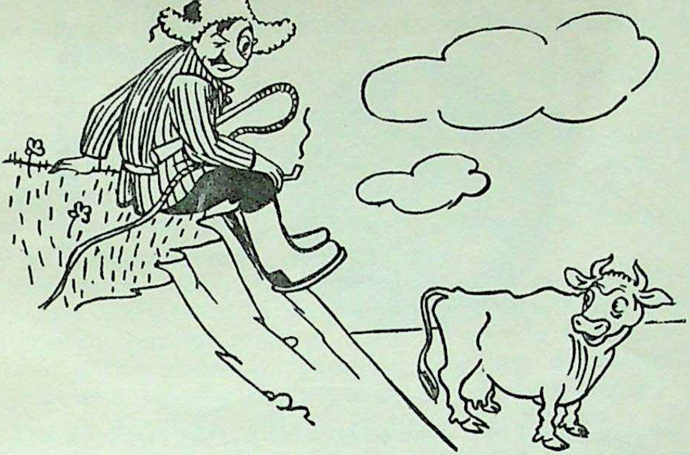
The answer depends on the location. When it is day in Moscow, it is night in Vladivostok. There is no paradox



here. Simply, "day" and "night" are relative notions and you cannot answer the question without referring to the place.

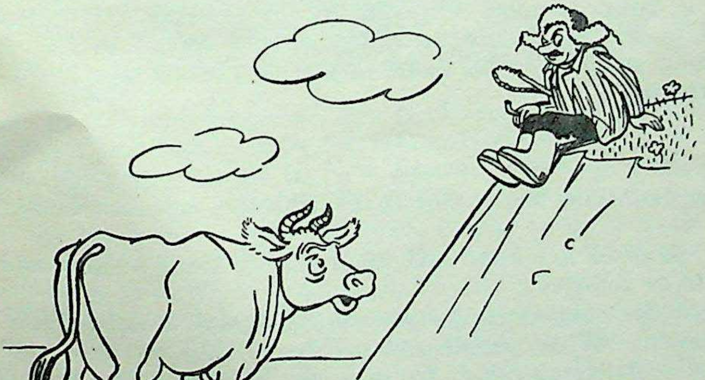
Who is Bigger?

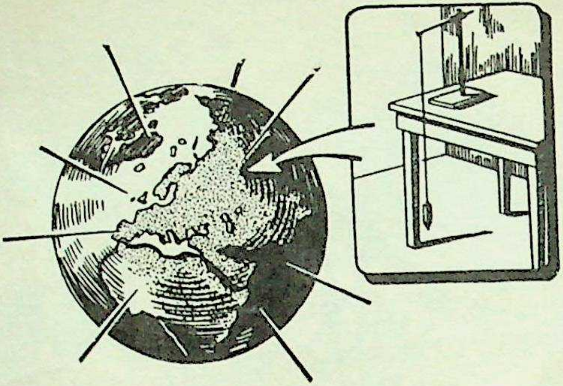
In the top drawing on the next page the cowherd is obviously bigger than the cow. In the lower drawing, the cow is bigger than the cowherd. This is no incongruity either. The two pictures were drawn from two different points—one closer to the cow, and the other closer to the cowherd. It is not the true dimensions of an object that are essential for a drawing, but the angle at which they are viewed. And these angular dimensions of objects are quite obviously relative. It is senseless to speak about angular dimensions of objects unless the latter are pinpointed in space. For instance, there is no sense in saying that a tower is seen from an angle of 45°. But if you say that a tower 15 metres away from you is seen at an angle of 45°, that is quite reasonable. It follows, moreover, that the tower is 15 metres high.



The Relative Appears Absolute

If we shift our point of observation slightly, the angular dimensions will also change slightly. That is why angular measurements are often used in astronomy. Stellar maps are supplied with angular distances between the stars, i.e., the angles at which the distance between the stars is seen from the Earth.





Regardless of our movements on Earth, and regardless of our point of observation, we shall always see the stars at one and the same distance from each other. This is due to the tremendous, inconceivably great distances that separate us from the stars. Compared to them our movement on Earth from point to point is so insignificant that we may easily disregard it. Therefore, in this case angular distances may be accepted as absolute distances.

If we take the rotation of the Earth round the Sun into account, the change of the angular measurement becomes noticeable, though hardly significant. The picture would change radically, however, if we were to shift our observation point to some star—Sirius, for example. All angular measurements would be different, and we would find the stars, which were far apart in our sky, closer together, and vice versa.

The Absolute Turns Out to Be Relative

We often say "up" and "down". Are these notions absolute or relative?

At different times people gave different answers to this question. When people did not know that our Earth was round and imagined it to be as flat as a pancake, the vertical direction was regarded as an absolute concept. It was assumed that the vertical direction was one and the same at all points of the Earth's surface and that it was quite natural to speak of the absolute "up" and the absolute "down".

When it was discovered that the Earth was round, the notion "vertical" collapsed.

Indeed, the Earth being round, the direction of a vertical line depends essentially on the position of the point on the Earth's surface through which that line passes.

At different points of the globe the vertical direction will be different.

Since the notions of "up" and "down" thus lost sense, unless the exact point of the Earth's surface was specified, the absolute became relative. There is no one vertical direction in the Universe. Therefore, for any direction in space we may specify the point on the Earth's surface at which this direction will be vertical.

"Common Sense" Protests

All this appears obvious to us today and we do not doubt it in the least. Nevertheless, we know from history that it has not been easy for man to realize the relativity of "up" and "down". People are inclined to ascribe absolute sense to concepts if their relativity is not evident from everyday experience (as in the case of "right" and "left").

Let us recall the absurd objection to the fact that the Earth was round, which came down to us from the Middle Ages: how can people walk upside-down?!

This argument is wrong because it overlooks the relativity of the vertical direction that stems from the Earth being round.

If we did not recognize the relativity of the vertical direction and took it to be absolute in Moscow, for example, then, naturally, people in New Zealand would be walking upside-down. But bear in mind that for New Zealanders we Muscovites, too, are walking upside-down. There is no contradiction in that at all, since the vertical direction is not really an absolute concept, but a relative one.

We begin to feel the true meaning of the relativity of vertical directions only when we consider two points sufficiently far apart on the Earth's surface—Moscow and New Zealand, for example. If, on the other hand, we take two points that are close to each other—two houses in Moscow, for example—we are justified in considering all verticals in them to be practically parallel, that is, absolute.

It is only when we deal with areas comparable in size to the Earth's surface that the attempt to apply an absolute vertical leads to absurdities and contradictions.

The examples discussed above show that many of the concepts that we use in our everyday life are relative, that they make sense only when we specify the conditions of observation.

Chapter Two

SPACE IS RELATIVE

One and the Same Place or Not?

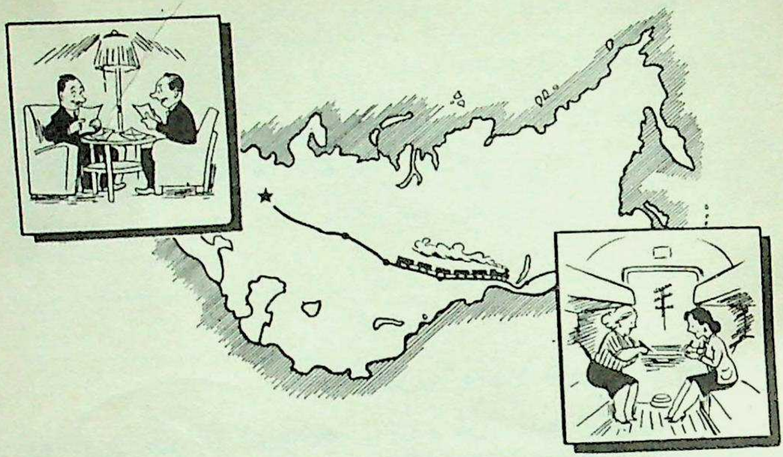
Often we say that two events occurred in one and the same place and tend to ascribe absolute meaning to our assertion. But in reality it means nothing. It amounts to saying, "It is five o'clock now," without specifying where—in Moscow or Chicago.

To understand this properly, let us imagine that two travellers have arranged to meet every day in one and the same compartment aboard the Moscow-Vladivostok express train and write letters to their husbands. Their husbands would hardly agree if we told them that their wives met at one and the same point in space. They would say, and not without reason, that these points were hundreds of kilometres apart. Did they not get the letters from different cities—Yaroslavl, Perm, Sverdlovsk, Tumen, Omsk, and Khabarovsk successively.

These two events—writing letters on the first and on the second day of the journey—occurred in one and the same place from the point of view of the wives, and in places hundreds of kilometres apart from the point of view of their husbands.

Who was right—the wives, or their husbands? We have no grounds to side with either of them. It is quite evident to us that the concept "at one and the same point in space" is relative.

Similarly, the assertion that two stars in the sky coincide makes sense only if it specifies that they have been observed from the Earth. Two events may be said to coincide in space only if we mention the bodies in relation to which the events are located.



Thus, the concept of position in space is also relative. When we speak of the position of a body in space, we always imply its position relative to other bodies. If we do not mention other bodies in our answer to a question concerning the position of a given body, the question will lack sense.

How a Body Really Moves

It follows that the concept of "shifting of a body in space" is also relative. If we say that the body has shifted in space, we mean that it merely changed its position relative to other bodies.

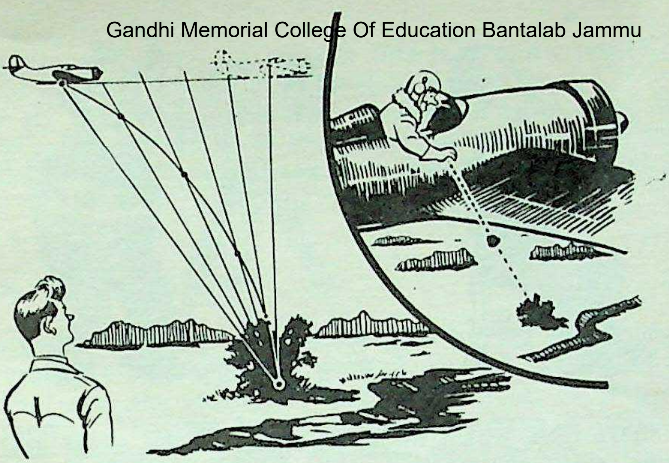
If we observe the motion of a body from various points that alter their relative positions, we shall notice that its motion varies.

A stone dropped from a flying plane falls in a straight line relative to the plane, but describes a curve, known as a parabola, relative to the Earth.

How does the stone travel in reality?

There is as little sense in that question as there is in the one about the angle at which the Moon is seen in reality. If observed from the Sun, or from the Earth?

The geometrical shape of the curve along which a body moves is just as relative as the photograph of a building. Just as we obtain different photographs when we snap a



building from the front and from the rear, so do we get different curves when following the flight of a stone from different points.

Are All Points of View Equivalent?

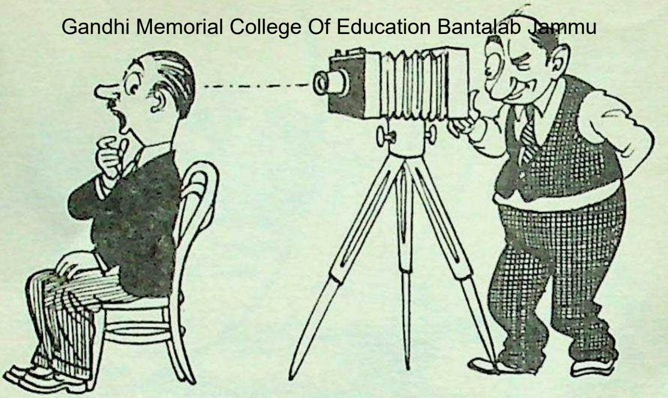
If we limited our interest when observing the motion of a body in space to a study of the trajectory (the curve along which the body moves), we would be guided in our selection of a place of observation by considerations of convenience and simplicity.

A good photographer, when he selects a spot for his camera, is concerned, among other things, with the aesthetic side of his picture, with its composition.

But in studying the motion of bodies in space our interest is broader. Not only do we want to know the trajectory, but also to predict the path of a body in the given conditions. In other words, we want to know the laws governing its motion—the laws that induce bodies to move one way or another.

When we examine the relativity of motion from this point of view, we find that not all positions in space are equivalent.

If we ask the photographer to snap us for an identification card, it is our face that we want photographed, and not the back of our head, which determines the position



in space from which he photographs us. No other position would meet our requirement.

The State of Rest Is Found!

The motion of bodies is influenced by external forces. A close examination of this influence will provide us with an entirely new approach to the problem of motion.

Let us assume that we have a body at our disposal which is not influenced by any external forces. This body will move in a different, more or less bizarre fashion, depending on the point of our observation. But it is obvious that the most natural position for the observer will be the one in which the body is simply at rest.

We can therefore now give a completely new definition of the state of rest, irrespective of the movement of the given body relative to other bodies. Thus, a body free from the influence of any external force is in a state of rest.

Inertial Frame

How can we bring about a state of rest? When can we be sure that a body is not influenced by any extraneous forces?

For that purpose, we must take that body as far away as we can from all the other bodies that might affect it.

We could, in our imagination, build a laboratory—a frame—of such inertial bodies, and discuss the properties of motion in observing it from this laboratory, which we would consider to be in the state of rest.

If the properties of motion observed in some other laboratory should differ from the properties of motion observed in our laboratory, we would be warranted to say that the first laboratory was moving.

Does the Train Move?

After we establish that motion in a moving laboratory is governed by laws different from those that prevail in the inertial one, the concept of motion will seem to have lost its relative character. We would then only have to imply the motion of relative inertia and refer to it as absolute.

But will the laws prevailing in an inertial laboratory change in every case when the laboratory is moved?

Let us board a train moving in a straight line at a uniform speed and observe the behaviour of bodies inside the carriage, comparing it with that in a motionless train.

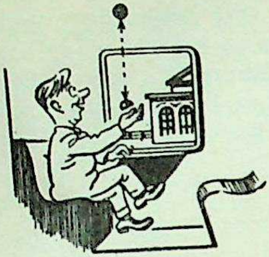
Our daily experience tells us that in a train travelling at a constant speed along a straight line the motion of bodies is the same as in a stationary train. A ball tossed vertically into the air in a moving train will invariably drop back into your hands rather than describe a curve as shown on page 20.

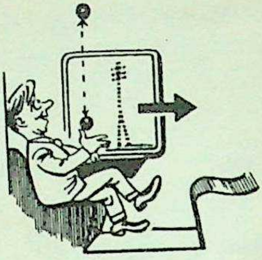
If we discount the jolting that is inevitable for technical reasons, everything inside a moving train behaves as if the train were at rest.

It is a different thing when the train reduces or increases its speed. In the first case we experience a jolt forward and in the second a jolt backward, quite distinct from a state of rest.

If a train moving with a uniform velocity changes its direction we also feel it at once. At a sharp right turn we will be pressed against the left side of the carriage, and vice versa at a left turn.

Summing up, we come to the conclusion that as long as a certain laboratory moves uniformly and rectilinearly relative to another laboratory that is in a state of rest, it is impossible to observe in it deviations from the behaviour of bodies in the latter laboratory. However, as soon as the motion of the moving laboratory changes (acceleration,





deceleration, change of direction) the effect is instantly felt in the behaviour of the bodies in it.

The State of Rest Is Lost for Ever

The amazing fact that a laboratory in uniform rectilinear motion has no effect upon the behaviour of the bodies in it, compels us to revise our conception of the state of rest. It develops that the state of rest and the state of uniform and rectilinear motion do not differ. A laboratory which moves uniformly and rectilinearly relative to the one that is in a state of rest may itself be considered in a state of rest. This means that there is not one absolute state of rest, but a countless number of various "states of rest". Hence, there is a countless number of laboratories "in a state of rest", all of them moving *uniformly and rectilinearly* relative to each other at various speeds.

Since the state of rest is relative and not absolute, we have to mention every time in relation to which of the countless laboratories moving uniformly and rectilinearly relative to each other we observe the given motion.

Thus, we have failed to make motion an absolute concept. In relation to what "state of rest" we observe the motion is a question that is for ever open.

We have thus come to the most important law of nature, usually called the principle of relative motion.

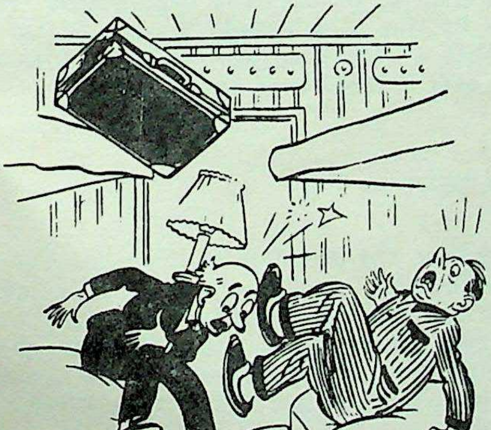
It says that the motion of bodies within frames that move uniformly and rectilinearly relative to each other is governed by the same laws.

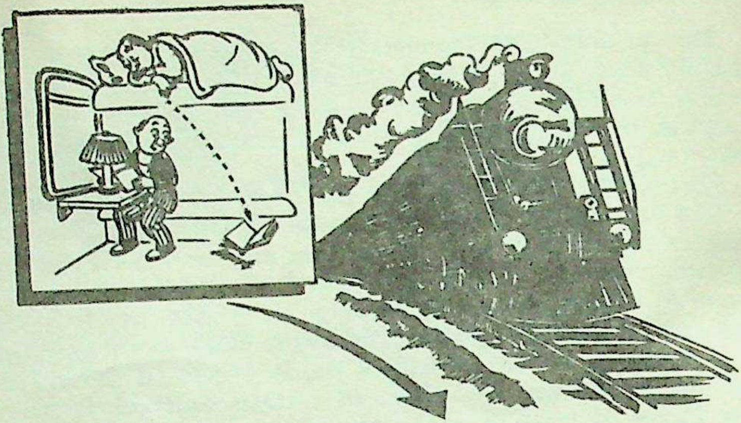
The Law of Inertia

The principle of the relativity of motion states that a body which is not acted upon by an external force may be either in a state of rest or in a state of rectilinear and uniform motion—a condition which physicists call the law of inertia.

However, in our daily life the operation of this law is veiled and does not directly manifest itself. By the law of inertia a body in a state of uniform and rectilinear motion should retain its motion for ever if no external forces act upon it. However, our observations show that even if we do not apply force to a body it is bound to come to a standstill.

The key to the riddle lies in the fact that all the bodies we see experience the effect of certain external forces—the forces of friction. The condition we need in order to observe the law of inertia—absence of external forces acting upon the body—is unavailable. However, by improving the conditions of the experiment, i.e., by reducing the forces of friction, we may approach the ideal condition required to observe the law of inertia, thereby proving that this law is also valid for motions observed in our daily life.





The discovery of the principle of the relativity of motion is one of man's greatest discoveries. Physics would never have been able to develop without it. We owe this discovery to the genius of Galileo, who boldly opposed Aristotle's teaching, dominant at that time and strongly supported by the Catholic Church. According to Aristotle motion was possible only if force was applied and would inevitably cease without it. Galileo proved the very contrary in a number of brilliant experiments. He showed that it was friction that brought moving bodies to a standstill, and that a body once put into motion would keep moving for ever if there were no friction.

Velocity Is Relative, Too!

It follows from the principle of the relativity of motion that the uniform and rectilinear motion of a body moving at a certain velocity is a meaningless concept, unless we specify in relation to which inertial frame that certain velocity is measured. The same may be said about the concept of longitude if we do not state from what meridian it is to be measured.

We thus find that velocity is also a relative concept. If we determine the velocity of one and the same moving body relative to different inertial frames we will get different results.

Yet each change of velocity, whether acceleration, deceleration or change of direction, is absolute in meaning and does not depend on the position of the frame from which we observe it.

Chapter Three

THE TRAGEDY OF LIGHT

Light Does Not Propagate Instantaneously

We have convinced ourselves of the principle of the relativity of motion and of the existence of a countless number of "inertial" frames. In the latter the laws governing the motion of bodies are similar. However, there exists a kind of motion which, at first glance, contradicts the principle we have established above. It is the propagation of light.

Light does not propagate instantaneously, although, indeed, its velocity is tremendous—300,000 km/sec!

This colossal velocity is hard to conceive, since in our everyday experiences we usually deal with far lesser speeds. The speed of the latest Soviet space rocket, for example, is a mere 12 km/sec. Of all the bodies we deal with, the Earth has the greatest speed in its rotation round the Sun. But even so, the speed of the Earth is only 30 km/sec.

Can the Velocity of Light Be Changed?

The colossal velocity of light propagation is something very extraordinary in itself. Much more striking is the fact that this velocity is strictly constant.

You can always accelerate or decelerate the motion of a body artificially. Even of a bullet. All you need to do is to place a box of sand in its path. Having pierced the box the bullet will lose its velocity.

It is different with light. The velocity of a bullet depends largely on the design of the rifle it is fired from and the properties of gunpowder, while the speed of light is always the same no matter what its source.

Let us place a plate of glass in the path of a beam of light. Since the velocity of light in glass is less than in vacuum, the beam will travel slower. However, having passed through the glass, the light regains the speed of 300,000 km/sec!

Light propagation in vacuum, as distinct from all other kinds of motion, has a very important property—it can neither be accelerated nor decelerated. Whatever changes the beam of light undergoes in matter, it propagates with the same velocity as soon as it emerges into vacuum.

Light and Sound

In this respect the propagation of light reminds us more of sound propagation than of the usual motion of bodies. Sound is the vibration of the medium in which it propagates. Therefore, the velocity of sound depends on the properties of the medium and not on the properties of the sound-producing body: sound velocity cannot be increased or decreased any more than light velocity, even by passing the sound through other bodies.

If we place a metal barrier in its path, the sound will change its velocity inside the barrier, but as soon as it emerges again into its initial medium it will regain its initial velocity.

Let us place an electric bulb and an electric bell under the glass hood of an air pump and proceed to pump out the air from under the hood. The sound of the bell will get weaker and weaker, until it becomes altogether inaudible. The bulb, on the contrary, will radiate light as usual.

This experiment proves that sound propagates in a material medium, while light propagates even in vacuum.

Therein lies their essential difference.

The Principle of Relativity of Motion Seems to Be Shaken

The colossal but not infinite velocity of light in vacuum brings us into conflict with the principle of relativity of motion.

Imagine a train hurtling along at a tremendous speed of 240,000 km/sec. We are riding in the head carriage, and an electric bulb is switched on in the tail carriage. Let us see what results we would get if we measured the time necessary for the light to travel from one end of the train to the other.

It would seem that this time would differ from the one we would obtain if the train were at rest. Indeed, relative to a train moving at 240,000 km/sec the light should travel at a speed of only 300,000 — 240,000 = 60,000 km/sec. It is as if the light has to catch up with the head carriage. If we place the bulb at the head of the train and measure the time necessary for the light to reach the tail carriage, it would seem that its velocity in the direction opposite to the movement of the train should be 240,000 + 300,000 = 540,000 km/sec. The light and the tail carriage move towards each other.

Thus, it appears that in a moving train light should propagate at different velocities in different directions, while in a train which is at a standstill the velocity of light is the same in both directions.

It is quite different with a bullet. Whether fired in the direction of the train's movement or against it, the velocity of the bullet relative to the walls of a carriage will be the same—equal to the bullet's velocity in an unmoving train.

"Absolute state of rest"

The fact is that the velocity of a bullet, depends on the speed of the rifle, while the velocity of light, as we have already said, does not change with the change in the speed at which the bulb is travelling.

Our argument seems to demonstrate that the propagation of light contrasts sharply with the principle of the relativity of motion. A bullet flies at one and the same velocity relative to a moving train and a train at rest, while in a train travelling at 240,000 km/sec light apparently propagates five times as slow in one direction and 1.8 times as fast in the opposite direction as in an unmoving train.

It would seem that a study of light propagation should enable us to establish the absolute speed of a moving train.

There is hope that we might establish the concept of the absolute state of rest by means of the phenomenon of light propagation.

The frame in which light propagates in all directions at the same constant velocity, 300,000 km/sec, may be said to be in a state of absolute rest. In any other frame which moves uniformly along a straight line relative to the first one, the velocity of light should be different in different directions. In that case relativity of motion, relativity of velocity, and relativity of the state of rest, which we have established above, do not exist.

The Ether of Space

How is this to be conceived? At one time physicists applied the analogy between the phenomena of sound and light propagation to introduce a special medium, which they called ether, in which light propagated in the same way as sound travelled in air. They assumed that bodies moving through ether no more propelled the latter than a floating box made of narrow slats of wood propels the water.

If our train is motionless relative to the ether, then light will propagate in all directions with the same velocity. The motion of the train relative to the ether will manifest itself at once in the fact that the velocity of light will be different for different directions.

However, this introduction of ether, a medium whose vibration we observe in the form of light, gives rise to a number of pointed questions. To begin with, the hypothesis itself is obviously artificial. Indeed, we can study the properties of air not only by observing the propagation of sound in it, but also by various physical and chemical methods of research. Meanwhile, due to some mysterious reason, ether takes no part in most of the phenomena. Air density and pressure are easily measured by the crudest methods. Yet all the attempts to learn something of the density and pressure of ether came to nought.

The position is rather ridiculous.

All phenomena of Nature can, of course, be "explained" by introducing some special liquid possessing the desired properties. But the difference between the genuine theory of a phenomenon and a simple paraphrase of well known facts with scientific terms lies precisely in the fact that a lot more follows from the theory than we get from the facts on which it is based. Take, for example, the conception of atom. It was through chemistry that it was introduced into science, but our notion about atoms enabled us to explain and predict a great number of phenomena having no relation to chemistry.

The concept of ether may be justifiably likened to the explanation which a savage would have given the gramophone, to the effect that a special "gramophone spirit" was imprisoned in the mysterious box.

Such "explanations" explain nothing.

Physicists had an unfortunate experience of that kind prior to ether. There was a time when they "explained" the phenomenon of combustion by the properties of a special liquid which they called flogiston, and the phenomenon of heat by the properties of another liquid—hetorode. These liquids, by the way, were no less elusive than ether.

Difficult Situation

But the main difficulty lies in the fact that violation of the principle of relativity of motion by light propagation should have inescapably led to the violation of the same principle by all other bodies.

After all, any medium offers resistance to the motion of bodies. Therefore, the displacement of bodies in ether should also involve friction. The movement of a body should slow down, and finally it should come to a standstill, the state of rest. Meanwhile, the Earth is rotating round the Sun for many thousands of millions of years (according to geological facts) and shows no trace of slowing down due to friction.

Thus, by trying to explain the strange behaviour of light along a moving train by the presence of ether we have stumbled into a blind alley. The notion about ether does not eliminate the contradiction between violation of the principle of relativity by light and observance of it by all other motions.

Experiment Should Decide

What is to be done with this contradiction? Before voicing our considerations on this score let us turn to the following circumstance.

The contradiction between light propagation and the relativity of motion has been derived by us exclusively through a mental construction.

It is true, we repeat, that this construction was very convincing. But if we confine ourselves to reasoning alone we shall liken ourselves to an ancient philosopher who tried to produce the laws of Nature out of his head. The inevitable danger arises that the world thus construed may one day develop to be very much unlike the real one.

Experiment is the supreme judge of all and every physical theory. Therefore, not confining ourselves to arguments as to how light propagates in a moving train, we shall turn to experiments showing how it actually propagates in these conditions.

Our experiment is facilitated by the fact that we ourselves live on a moving body. Rotating round the Sun, the Earth does not move along a straight line and cannot therefore be in a permanent state of rest relative to any other frame.

Even if we take a frame relative to which the Earth is motionless in January, it is certain to be in motion in July, since the direction of the Earth's rotation round the Sun changes. Therefore, studying light propagation on the Earth we, in fact, study it within a frame that moves at a speed of 30 km/sec, something quite considerable in our conditions. The rotation of the Earth round its axis of the order of nearly half a kilometre per second may be ignored.

Are we justified, however, to liken our globe to the moving train which we discussed above and which led us into a blind alley? The train moves in a straight line with a uniform velocity, while the Earth's motion is orbital. Yes, we are justified to do so. The Earth may well be considered to be moving uniformly along a straight line in that infinitesimal fraction of a second which it takes light to pass through the points of observation. The margin of error is so very insignificant that it cannot be detected.

But since we have likened railway train and Earth, it would be natural to expect that light on the Earth would behave just as strangely as it did in our train, i.e., that it would turn out to be in different directions at different velocities.

The Principle of Relativity Triumphs

An experiment of this kind was made in 1881 by Albert Michelson, one of the 19th-century greatest experimenters, who measured, with a high degree of accuracy, the velocity of light travelling in different directions. To detect the expected slight differences in velocity Michelson used very precise and ingenious experimental equipment. The accuracy of his experiment was so high that he would have been able to detect far smaller differences in velocity than the anticipated ones.

The Michelson experiment, later repeated under various conditions, led to quite unexpected results. In a moving frame light propagated guite differently from what we had inferred. Michelson discovered that on the rotating Earth light travelled in all directions at the same constant velocity. In this respect, light propagation reminds us of the flight of a bullet: it is independent of the motion of the frame and its velocity relative to the walls of the frame is the same in all directions.

Michelson's experiment thus proved that *contrary to our inference* the phenomenon of light propagation, far from contradicting, fully agrees with the principle of relativity of motion. In other words, all our reasoning on page 26 turns out to be erroneous.

Out of the Frying-Pan into the Fire

We have cast off the uneasy contradiction between the laws of light propagation and the principle of relativity of motion. The contradiction was only a seeming one due to our erroneous reasoning. Why did we make our mistake?

For nearly a quarter of a century, from 1881 to 1905, physicists racked their brains over this problem. Yet all their explanations inevitably led to new contradictions between theory and practice.

If the source of sound and the observer travel in a cage made of thin rods, the observer will feel a strong wind. If we measure sound velocity relative to the cage, it will be less in the direction of motion of the cage than in the opposite direction. However, suppose we place the source of sound in a carriage in which all the windows and doors are tightly shut and measure its velocity. We shall discover that since the air inside the carriage is not affected by the movement of the carriage, the speed of sound in it will be the same in all directions.

If we take light instead of sound, we could make the following assumption to explain Michelson's experiment. The Earth does not leave the ether undisturbed, as does the cage of thin rods, when hurtling through space. On the contrary, let us assume that the Earth carries the ether along with it, and that in its movement it comprises a single whole with the ether. In that case the outcome of Michelson's experiment would be quite understandable.

But this assumption conflicts with a great number of other experiments, such, for example, as propagation of light in water flowing through a tube. If our assumption about ether being carried along by the Earth were right, then by measuring the velocity of light in the direction of the flow we would obtain a velocity equal to the velocity of light in motionless water plus the velocity of the water flow. But as a result of our measurements we get a lower velocity than we should if our assumption were right.

We have already mentioned the extremely strange phenomenon of bodies not experiencing any friction to speak of when passing through ether. But if they not only pass through ether but carry it along with them, the friction should be greater.

Thus, all attempts to pass over the contradiction that arose after the unexpected outcome of Michelson's experiment failed.

Let us sum up.

Michelson's experiment reconfirms the principles of relativity of motion not only for ordinary bodies, but also for light propagation and, hence, for all natural phenomena.

As we have already seen, the relativity of velocity stems directly from the principle of relativity of motion. Different frames moving relative to each other should have different speeds. But, on the other hand, light velocity of 300,000 km/sec is the same for all the frames. Therefore, it is absolute and not relative!

Chapter Four

TIME IS RELATIVE

Is There Really a Contradiction?

At first glance it may seem that we are dealing with a purely logical contradiction. The constancy of the velocity of light propagating in all directions is ample proof of the principle of relativity. At the same time, the velocity itself is absolute.

Let us recall, however, how the medieval man treated the fact that the Earth was round. To him the roundness of the Earth conflicted with the force of gravity, since he thought that all objects had to roll "off" the Earth's surface. Yet we know perfectly well that there is no logical conflict at all. Simply, the concepts of "up" and "down" are relative, and not absolute.

The same holds true for the propagation of light.

It would have been futile to look for a logical contradiction between the principle of relativity of motion and the absoluteness of the velocity of light. The contradiction appears when we introduce other assumptions, much in the way people in the Middle Ages had done when they refuted that the Earth was round by treating the concept of "up" and "down" as an absolute concept. Their absurd belief stemmed from insufficient experience: people travelled very little at the time and knew only small areas of the Earth's surface. Evidently, something similar happened to us: our insufficient experience made us believe something relative to be absolute.

What?

To spot our mistake we shall from now on accept nothing but propositions based on experiment.

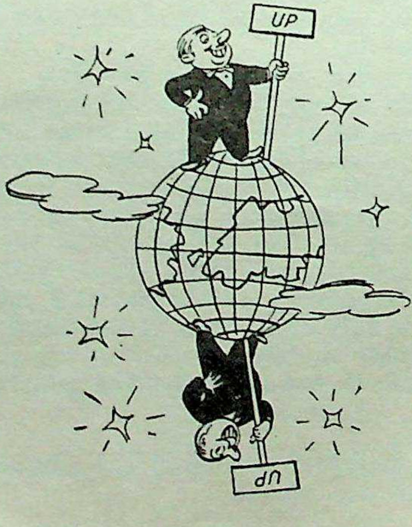
Imagine a train 5,400,000 km long moving with a uniform velocity of 240,000 km/sec along a straight line.

Suppose a lamp is switched on at some given instant of time somewhere in the middle of the train. And suppose the automatic doors in the front and rear carriages open the moment the light of the bulb reaches them. What will the people on board the train and those standing on the station platform see?

In answering this question we will, as agreed, abide solely by experimental data.

The people in the middle of the train will see the following: since, according to Michelson's experiment, light travels relative to the train at the same velocity in all directions—300,000 km/sec, it will reach the rear and front carriages simultaneously, 9 seconds later (2,700,000 : 300,000) and both doors will open at the same time.

Relative to the station platform the light also travels at a speed of 300,000 km/sec, but the rear carriage moves to meet the light beam. Therefore, the beam of light will reach the rear carriage after $\frac{2{,}700{,}000}{300{,}000+240{,}000}=5$ seconds. The beam must catch up with the front carriage and, therefore, will reach it 45 seconds later, $\frac{2{,}700{,}000}{300{,}000-240{,}000}$.



It will seem to the people on the platform that the doors open at different times—the rear door first and the front door 45—5=40 seconds later.

Thus, two absolutely identical events—opening of the front and rear doors of the train—will happen at the same time for the people on board the [illegible] 40-second interval for those on the platform.

Contrary to Common Sense?

Is there any contradiction in this? Perhaps the fact we have discovered is as absurd as saying that an alligator measures two metres from head to tail and one metre from tail to head.

Let us try and see why the result we have obtained seems absurd in spite of the fact that it conforms with experiments.

Hard as we may think, we shall never find any logical contradiction in the fact that the two phenomena which happened simultaneously for the people in the train were 40 seconds apart for the people on the platform.

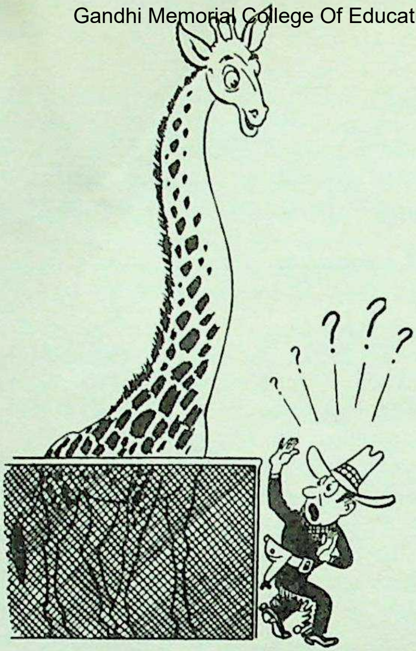
Our conclusions are a howling contradiction to "common sense", that is the only thing we can say to console ourselves.

But remember how the "common sense" of the medieval man revolted against the fact that the Earth rotated round the Sun? Indeed, the medieval man's experience told him indisputably that the Earth was standing still and that the Sun rotated round it. And was it not "common sense" that we have to "thank" for the ridiculous proof that the Earth could not be round? The conflict of "common sense" with a real fact was ridiculed in a well-known joke about a cowboy who exclaimed, "It can't be!" when he saw a giraffe in the Zoo.

So-called "common sense" is no more than a summing up of the concepts and habits formed in everyday life.

It represents a certain level of apprehension reflecting the extent of our experience.

The difficulty of perceiving and understanding that the two events occurring simultaneously on the train are 40 seconds apart when seen from the platform is very much like the difficulty the cowboy had when he saw the giraffe. Like the cowboy had never seen the animal, so have we never travelled at speeds anywhere close to the fantastic speed of 240,000 km/sec. It is not surprising that physicists encounter such fantastic speeds since they observe facts which considerably differ from the things we are accustomed to in our everyday life.



The unexpected outcome of Michelson's experiment furnished physicists with new facts and forced them to re-examine—in defiance of "common sense"—such, it would seem, obvious and commonplace concepts as simultaneity of two events.

It would have been simpler, of course, to deny the new phenomena on the grounds of "common sense", but if we did, we would liken ourselves to the cowboy who wouldn't believe his eyes when he saw a giraffe.

Time Shares the Fate of Space

Science does not hesitate to come into conflict with so-called "common sense". What science fears most is inconsistency between existing concepts and new experimental data, and if ever that occurs it smashes the existing conceptions and raises our knowledge to a higher level.

We thought that two simultaneous events were simultaneous within any frame. Our experiment proved, however, that we were wrong. It applied solely in the case when the frames were in a state of rest relative to each other. If, on the other hand, two frames were in motion relative to each other, the events occurring simultaneously in one of them should be regarded as occurring at different times in the other. The concept of simultaneity becomes relative; it has sense only if we specify the motion of the frame in which the events are observed.

Let us recall the example of the relativity of angular distances on page 11. Let the angular distance between two stars observed from the Earth be zero, due to the two stars being aligned. In our everyday life we shall never come into conflict with the assumption that this is an absolute truth. It is different if we go outside the solar system and observe the same two stars from some other point in space. We would find the angular distance quite distinct from zero.

The fact, quite obvious to our contemporaries, that two stars which are aligned when observed from the Earth may not be aligned when observed from other points in space, would have appeared absurd to the medieval man who conceived the sky as a cupola sprinkled with stars.

Let us assume that we were asked whether, apart from frames of all kinds, the two events really occurred simultaneously. Unfortunately, this question has no more sense than the one whether, regardless of all points of observation, the two stars are really aligned. The fact is that simultaneity depends not only on the two events but also on the frame from which we observe them, just as alignment of the two stars depends not only on their position, but also on the point from which they are observed.

As long as man dealt with speeds that were insignificant compared with the velocity of light, the relativity of the concept of simultaneity was unknown to him. It was only when we examined motion at velocities comparable to the velocity of light that we were compelled to re-examine our concept of simultaneity.

In the same way, people had to revise their conception of "up" and "down" when they began to travel over distances comparable with the dimensions of the Earth. Before that the conception of the Earth being flat had not, of course, conflicted with experience.

True, we are not able to travel at velocities anywhere near the speed of light and to observe all the facts we have just discussed, which are paradoxical from the standpoint of our old concepts. But thanks to modern experimental techniques we are able to reveal these facts conclusively in a number of physical phenomena.

Time thus shares the fate of space! The words "at one and the same time" are just as meaningless as the words "in one and the same place".

The time interval between two events, like distance between them in space, has to be supplemented by a reference to the frame in relation to which it is defined.

The discovery that time is relative radically changed man's ideas about Nature. It represents one of the greatest victories of human reason over backward centuries-old conceptions. It is comparable only to the revolutionary change occasioned in human notions by the discovery that the Earth is round.

The discovery of the relativity of time made in 1905 by the greatest 20th-century physicist, Albert Einstein (1880-1955), placed him, then a 25-year-old young man, among the giants of human thought—Copernicus, Newton and others, the trail blazers in science.

Lenin called Albert Einstein one of the "great transformers of natural science".

The theory of the relativity of time and its corollaries are usually known as the special theory of relativity. It is not to be confused with the principle of the relativity of motion.

Velocity Has Its Limits

Before the Second World War the speed of aircraft was far below the speed of sound. Today we have supersonic aircraft. Radio waves propagate at the velocity of light. Could we perhaps create "superlight" telegraphy to send signals at velocities greater than the velocity of light? No, that is an impossible thing to do.

Indeed, if we could transmit signals at infinite velocities we would be able to establish simultaneity of any two events synonymously. We would say that these two events happened simultaneously if the infinitely fast signal about the first event arrived at the same instant as the signal about the second event. Thus, simultaneity of the two events would have acquired absolute character independent of the motion of the frame to which this assertion applies.

But since the experiment disproves the absolute nature of time we conclude that signal transmission cannot be instantaneous. The velocity of transmission from one point in space to another cannot be infinite; in other words, it cannot be greater than some finite value, called the limiting speed.

This limiting speed concurs with the light velocity. Indeed, according to the principle of the relativity of motion the laws of Nature will be the same for all the frames of reference moving relative to one another (with a uniform velocity along a straight line). The assertion that no velocity can be greater than the given limit is also the law of Nature and, therefore, the value of the limiting speed should be exactly similar in different frames of reference. The light velocity, as we know, possesses the same qualities. Thus, the speed of light is not merely the speed of propagation of a natural phenomenon. It plays the important part of being the limiting velocity.

The discovery of the existence in the Universe of the limiting velocity is one of the greatest triumphs of human genius and of the experimental capacity of mankind.

In the 19th century physicists were unable to perceive that the limiting speed existed and that its existence could be proved. Moreover, if they had stumbled upon it by chance in their experiments, they would not have been sure that it was a law of Nature and not merely the effect of their limited experimental capacity.

The principle of relativity reveals that the existence of the limiting velocity lies in the very nature of things. To assume that technological development will enable us to attain velocities greater than the velocity of light is just as ridiculous as to suggest that the absence of points on the Earth's surface more than 20 thousand kilometres apart is not a geographical law, but the upshot of our limited knowledge, and to hope that some day, when geography makes further advances, we shall be able to find points on the Earth that are still farther apart.

Light velocity plays such an exceptional part in Nature exactly because it is the limiting velocity for the propagation of anything. Light either outstrips all other phenomena, or at least arrives simultaneously with them.

If the Sun split in two and formed two stars, the motion of the Earth would, naturally, suffer a change as well.

The 19th-century physicist, who did not know that the limiting velocity existed in Nature, would certainly assume that the Earth changed its motion instantly after the Sun split in two. Yet it would have taken light all of eight minutes to cover the distance from the split Sun to the Earth.

The change in the Earth's rotary motion would begin eight minutes after the Sun split up. Until that moment, the Earth would continue to move as if the Sun had not split. Anything that may occur with or on the Sun will affect neither the Earth nor its motion until eight minutes later.

The limiting velocity of signal propagation naturally does not deprive us of the possibility of establishing simultaneity of two events. All we have to do is to note the time lag of the signal. That is the usual practice.

This method of establishing simultaneity of action is quite compatible with the relativity of this concept. Indeed, to subtract the difference in time we must divide the distance between the two spots where the events occurred by the velocity of the light signal. On the other hand, when we earlier discussed the sending of letters from the Moscow-Vladivostok express train we saw that the location of a spot in space is also quite relative.

Earlier and Later

Let us assume that in our train with the lamp, which we shall call the Einstein train, the automatic device has failed and people in the train noticed that the front door opened 15 seconds earlier than the rear one. Conversely, the people on the station platform will notice that the rear door flew open 40—15=25 seconds earlier. An event that occurred earlier in one frame, would take place later for the other.

It may occur to us that this relativity of the concepts of "earlier" and "later" should have its limits. It is not likely, after all (from the point of view of any frame), that a baby was born prior to the birth of its mother.

Suppose a spot is formed on the Sun. Eight minutes later it is detected by an astronomer observing the Sun through the telescope. Anything the astronomer does after that will be absolutely later than the appearance of the spot—"later" from the standpoint of any frame from which the Sun and the astronomer are observed. On the contrary, everything that happens to the astronomer earlier than eight minutes before the appearance of the spot (the light signal of this event reaching the earth before the appearance of the spot) takes place absolutely earlier.

If, for example, the astronomer put on his glasses at some instant between these two limits, the time relation between the appearance of the spot and the putting on of the glasses would no longer be absolute.

We may move relative to the astronomer and the spot on the Sun in such a way as to observe the astronomer putting on his glasses earlier or later than or at the same time with the appearance of the spot, depending on the speed and direction of our movement.

The principle of relativity thus demonstrates that three types of time relations exist between events—absolutely earlier, absolutely later and neither earlier nor later, or, to be more accurate—earlier or later relations, depending on the frame of reference from which the events are observed.

Chapter Five

CAPRICIOUS CLOCKS AND RULERS

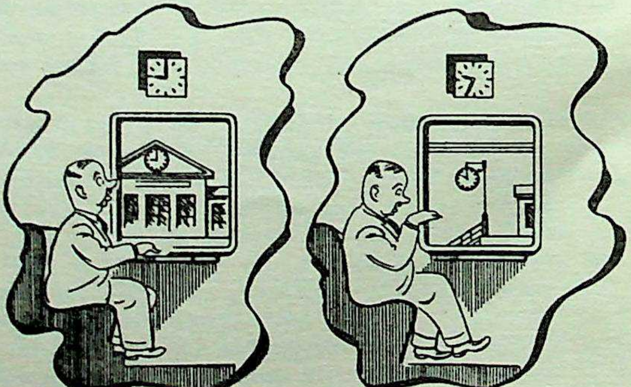
We Board the Train Again

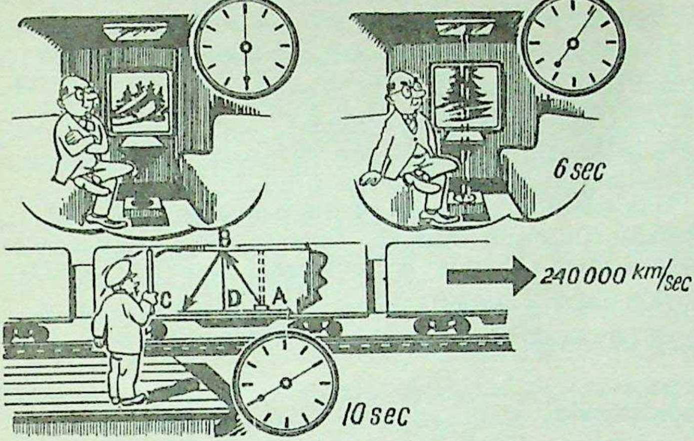
We are riding in the Einstein train along an endless railway. The distance between two stations is 864,000,000 km. It will take the train travelling at 240,000 km/sec one hour to cover this distance.

There are clocks at both stations. A traveller boarding the train at the first station sets his watch by the station clock. On arriving at the second station he is surprised to find that his watch is slow. At the repair shop he was told that his watch was in good order.

What was the matter?

To make it out, let us assume that the traveller sends a beam of light to the ceiling from an electric torch placed on the floor of the carriage. A mirror on the ceiling ref-





lects the beam back to the torch. The beam path as seen by the traveller is shown in the upper section of the figure on this page. It looks quite different to the observer on the platform. During the time it takes the beam to travel from the torch to the mirror, the mirror itself will shift due to the motion of the train. During the time it takes the beam to travel back to the torch the latter will shift by the same distance.

We notice that to the observers on the platform the beam clearly travelled a greater distance than to those in the train. On the other hand, we know that the velocity of light is an absolute velocity and that it is the same for those riding in the train and those who observe it from the platform. We conclude therefore that a greater time interval elapsed at the station between the departure and return of the beam than in the train!

The relation is easy to calculate. Suppose the observer on the platform established that 10 seconds elapsed between the departure and return of the beam of light. During these 10 seconds the beam travelled $300,000 \times 10 = 3,000,000$ km. It follows that sides AB and BC of the isosceles triangle ABC are 1,500,000 km each. AC is evidently equal to the distance which the train travels in 10 seconds, i.e., $240,000 \times \times 10 = 2,400,000$ km.

Now it is easy to find the height of the carriage which is equal to BD, the height of triangle ABC.

Let us recall that in a right-angled triangle the square of the hypotenuse (*AB*) is equal to the sum of the squares of legs *AD* and *BD*. The equation $\sqrt{AB^2=AD^2+BD^2}$ helps us find that the height of the carriage $BD=\sqrt{(AB^2-AD^2}=\sqrt{1,500,000^2-1,200,000^2)}=900,000$ km. Quite a height that, although it is not too surprising, considering the astronomic dimensions of the Einstein train.

From the point of view of the passenger, the path travelled by the beam from the floor to the ceiling and back again is obviously double the height, that is, $2\times900,000=$ $=1,800,000$ km. It will take $\frac{1,800,000}{300,000}=6$ seconds for the beam to travel this distance.

Clock Paradox

While 10 seconds elapsed at the railway station, only 6 seconds passed on the train. This means that if the train arrived one hour after its departure according to the station clock, it travelled only $60\times\frac{8}{10}=36$ minutes by the passenger's watch. In other words, in an hour his watch was 24 minutes behind the station clock.

It is easily seen that the greater the speed of the train the greater the time lag difference.

Indeed, the closer the speed of the train approaches that of light the closer the leg *AD* indicating the path of the train approaches the hypotenuse *AB* indicating the path travelled in the same time by the beam. The relation of the leg *BD* to the hypotenuse decreases correspondingly. Yet it is this relation that represents the time relation of the train to the platform. By increasing the speed of the train to approach the velocity of light we can reduce the time in the train to an infinitesimal figure per hour of station time. At a speed equal to 0.9999 of that of light, for example, only one minute will elapse on the train in one hour of station time.

Consequently, all travelling clocks and watches lag behind timepieces in a state of rest. Does this contradict the principle of relativity from which we proceeded in our argument?

Would it mean that the clock which is faster than all other clocks is in a state of absolute rest?

No, this is not the case because the comparison between the watch in the train and the station clock was made under absolutely unequal conditions. Actually there were three clocks, and not two. The traveller had checked his time against two different clocks at two different stations. And, conversely, if there were clocks in the front and rear carriages of the train, the observer comparing the station clock against those on the train as it flashed by, would discover that the station clock was always behind.

Given that the train travels with a uniform velocity along a straight line relative to the station, we are justified to consider it to be stationary and the station to be moving. The laws of Nature operating in them should be the same.

Each and every observer who is motionless in relation to his timepiece will notice that it is other clocks moving relative to him that are fast and that the clocks are all the faster as the rate of their motion rises.

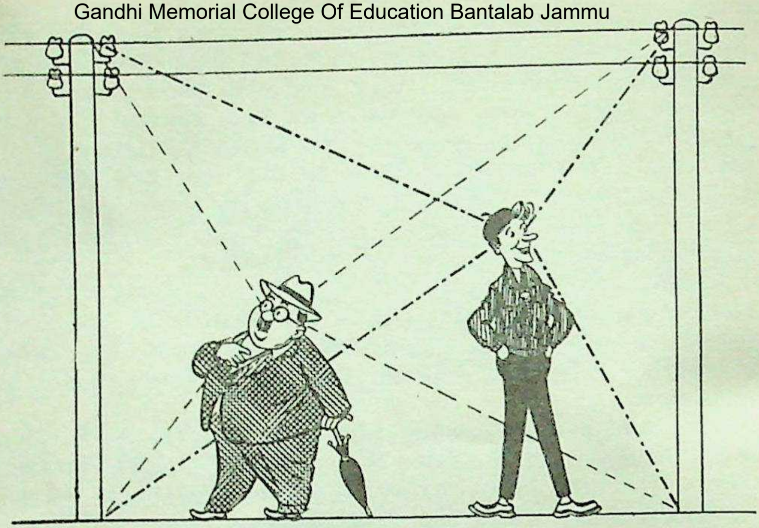
This may be compared to two observers standing beside different telegraph poles, each claiming that the pole he is standing at is seen from a greater angle than the other's.

Time Machine

Now, let us assume that the Einstein train travels along a circular railway and not in a straight line. It will then return after a certain time to its point of departure. As we have already established, the passenger will discover that his watch is slow, and the faster the train goes the slower his watch will be. By increasing the speed of the train we may reach a point where only a day passes for the passenger while a number of years elapse for the stationmaster. So many years may elapse, as a matter of fact, that on returning home to the station of departure after a day's journey (by his own watch), our passenger will learn that all his relatives and friends are long since dead.

During this journey by the circular railway the time of only two timepieces is compared—in the train and at the station of departure.

Is there anything in this that contradicts the principle of relativity? May we consider that the passenger is in a state of rest and that the station of departure is moving round the circle at the speed of the Einstein train? We would



then come to the conclusion that only a day passes for the people at the station, whereas many years elapse for the passengers in the train. This would be an incorrect inference. Here is why.

We have established above that a body may be considered stationary only if it does not experience the effects of an outside force. There is, it is true, more than just one state of rest. There is a countless number of them, and two stationary bodies may, as we know, move with constant speed along a straight line relative to each other. But the watch in the Einstein train speeding round the circular railway experiences the effect of centrifugal force, and we cannot, therefore, consider it to be in a state of rest. The difference between the times shown by the clock at the railway station and the watch in the train is absolute.

If two people whose watches show the same time part and then meet again, the watch of the one who was in a state of rest or moved uniformly in a straight line would be fast, for it would not have experienced the effects of any force.

A journey on the circular railway at a speed close to the velocity of light enables us to visualize Wells's time machine, if only to a limited extent, for on returning finally to our station of departure, we would step out of the carriage far into the future. We can go in the train to the future, but we cannot return to our past. Therein lies the big difference between the Einstein train and Wells's time machine.

It is no use hoping that we shall ever be able to travel into the past, no matter how far science progresses. If the reverse were true, we should be compelled to admit that truly absurd situations are possible in principle. Just imagine setting off into the past and landing in the utterly absurd predicament of a person whose parents have not yet been born.

Travel into the future involves no more than seeming contradictions.

Travelling to a Star

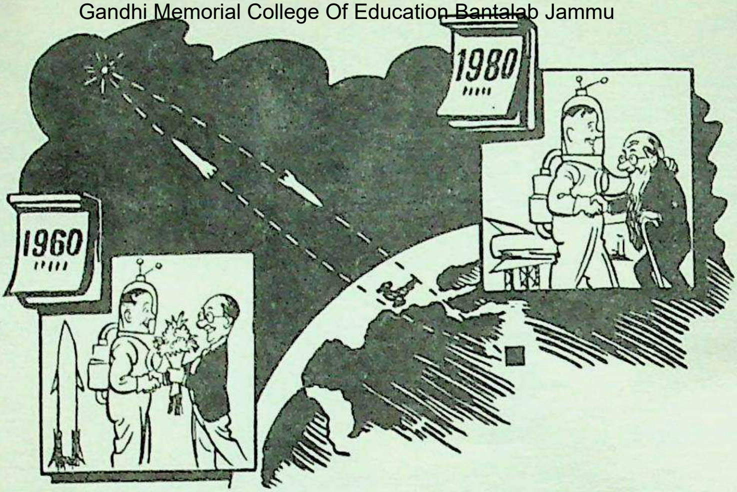
There are stars in the sky which are so far away from us that a beam of light takes 40 years to reach them. Since we already know that it is impossible to travel faster than the speed of light, we can well draw the conclusion that the star cannot be reached in less than 40 years. However, this inference is erroneous, because we did not consider the time contraction involved in motion.

Suppose we fly to the star in an Einstein rocket at a speed of 240,000 km/sec. For people on the Earth we will reach the star in $\frac{300,000\times 40}{240,000}=50$ years.

But for us, on board the rocket, flying time at the mentioned speed will shrink at a ratio of 10 to 6. Hence, we shall reach the star in $\frac{6}{10}\times 50=30$ years, and not in 50.

We can reduce this flying time indefinitely by raising the speed of our Einstein rocket until it approaches the speed of light. Theoretically, travelling at a sufficiently high speed we can reach the star and return to the Earth within a minute! But on the Earth 80 years will have passed just the same.

To all appearances, we thus possess a way of prolonging human life, though only from the point of view of other people, since man ages according to "his" own time. To our regret, however, this prospect is illusory if we take a closer look at it.



To begin with, the human body is not adapted to a state of prolonged acceleration exceeding noticeably the acceleration due to the Earth's gravity. It will require considerable time to accelerate to speeds close to the velocity of light. Calculations show that in six months of travelling at an acceleration equal to that due to gravity our gain will amount to a mere six weeks. If we prolong our trip the gain in time will increase sharply. Twelve months in a flying rocket will yield an additional gain of 18 months, two years of travelling will give a gain of 28 years, and if we spend three years in interplanetary travel we will gain more than 360 years!

Very comforting figures, don't you think?

The matter is less cheerful when we come to the expenditure of energy. A rocket weighing a mere one ton and flying with a speed of 260,000 km/sec (the speed required to "double" the time, i.e., for a year in the rocket to be equal to two on Earth) consumes 250,000,000,000,000 kilowatt-hours—an amount which it takes the world several months to produce.

However that is only what the rocket consumes in flight. We still have to figure out how much power it takes to accelerate our vehicle to the speed of 260,000 km/sec. More over, at the end of the flight the spaceship will have to be decelerated for a safe landing. How much power would that require?

It would still be 200 times as much as the amount we cited above, even if we had fuel enough to produce a jet escaping the engine at the highest speed possible—the speed of light. In other words, we would have to consume an amount of power that the world produces in several dozen years. Actually the jet escape velocity is scores of thousands of times less than the speed of light, making the power expenditure required for our imagined flight fabulously great.

Length Contraction

Time, as we have just seen, is not really an absolute concept. It is relative and requires precise indication of the frame from which observation is conducted.

Now let us turn to space. We found even before we discussed Michelson's experiment that space is relative. Yet despite the relativity of space we attributed an absolute character to the dimensions of bodies. In other words, we considered them to be the properties of the body which did not depend on the frame from which we made our observations. However, the theory of relativity forces us to abandon this conviction as well. Like our notion about time being absolute, it is a prejudice we have developed because we always deal with speeds infinitely smaller than the speed of light.

Let us imagine that the Einstein train rushes past a station platform 2,400,000 km long. The train travels from one end of the platform to the other in $\frac{2,400,000}{240,000}=10$ seconds by the station clock. But by the passengers' watches it will take the train only 6 seconds. The passengers will be fully justified to conclude that the platform is not 2,400,000 km but $240,000\times6=1,440,000$ km long.

The length of the platform, as we see, is greater from the point of view of the frame which is stationary relative to it, than from the point of view of the frame relative to which the platform is moving. All moving bodies contract in the direction of their movement.

However, this contraction does not prove at all that motion is absolute: the body acquires its true dimensions as soon as we view it from a frame that is stationary relative to the body. Likewise, the passengers will find that the platform has contracted, while the people on the platform will think that it is the Einstein train that has become shorter (ratio of 6 to 10).

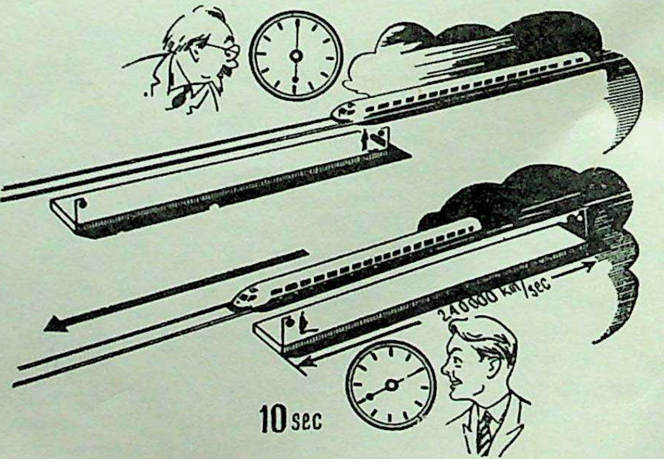
Nor will this be an optical illusion. All instruments used for measuring the length of a body will show it too.

In connection with this discovery we must now correct the inferences we made on page 34 about the time it takes for the doors to open in the Einstein train. When we were calculating the time when the doors open from the point of view of an observer on the platform, we assumed that the length of a moving train was the same as that of a stationary one. Yet the train was shorter for the people on the platform. Accordingly, the interval between the time the doors opened from the point of view of the station clock will actually amount to only $\frac{6}{10}\times 40=24$ seconds, and not 40 seconds.

Naturally, this correction is not essential for the conclusions we have made earlier.

The figures on page 52 show the Einstein train and the station platform as seen by observers at the station and in the train.

We see that in the figure on the right the platform is longer than the train and in the one on the left the train is longer than the platform.



Which one of these figures corresponds to reality?

The question is senseless, just as the question about the cowherd and the cow on page 11.

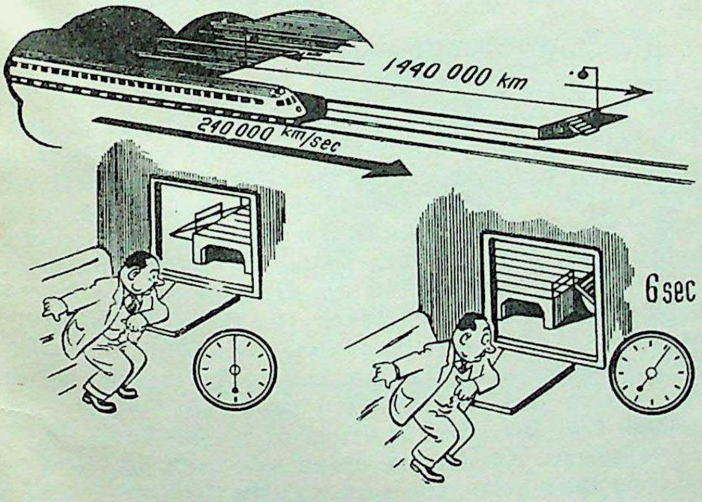
These two phenomena are "snapshots" of one and the same reality taken from different points of view.

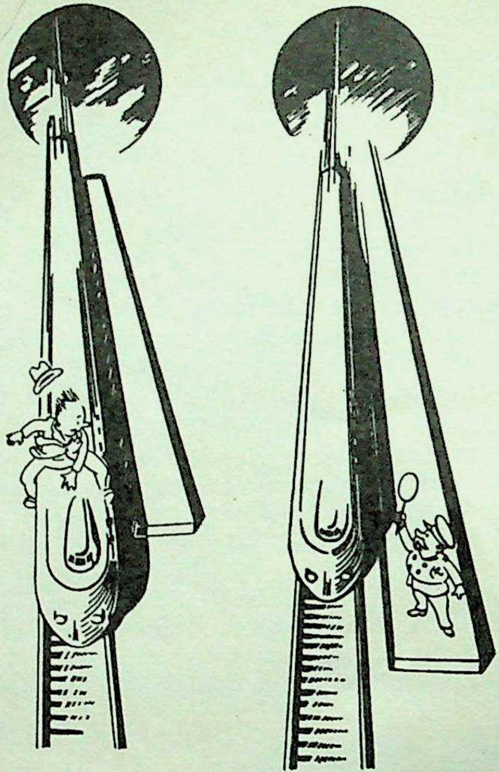
Capricious Speeds

What is the speed of the passenger relative to the railway tracks if he walks at 5 km/hr towards the head of a train travelling at 50 km/hr? It will evidently be 50+5=55 km/hr. Our answer is based on the velocity addition formula and we have no doubt whatsoever that it is correct. Indeed the train will have travelled 50 km an hour and the man on the train an additional 5 km. Hence the total of 55 km.

It is obvious that the existence of a limiting speed makes the law of the addition of velocities inapplicable universally to small and large speeds. If the passenger were travelling in the Einstein train at a speed of, say, 100,000 km/sec, his speed relative to the railway tracks would have to be 240,000+100,000=340,000 km/sec. But there is no such speed, because it exceeds the speed of light.

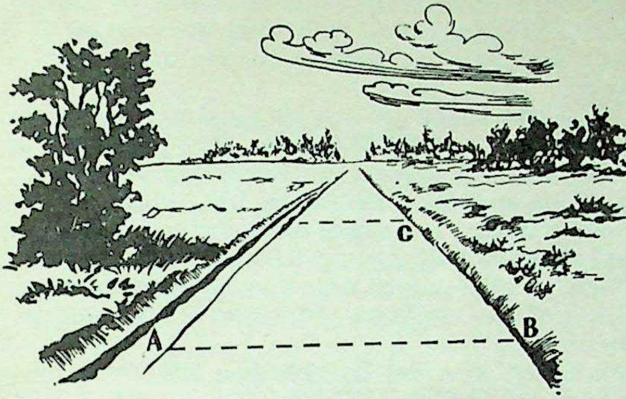
Consequently, the law of the addition of velocities, which





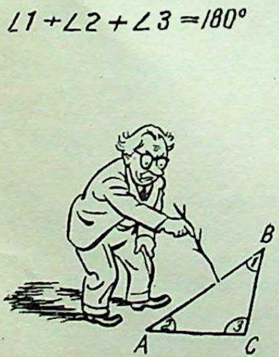
we use in our everyday life, is not entirely accurate. It applies only to speeds far lower than the velocity of light.

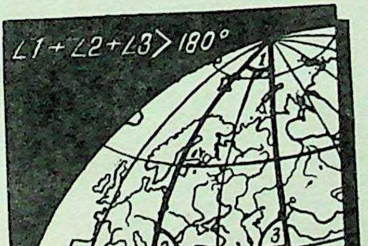
The reader, who is by now accustomed to all sorts of paradoxes in connection with the relativistic theory, will easily understand why the seemingly obvious reasoning, whereby we have just deduced the principle of addition of velocities, is inadequate. We added the distance travelled by the train in one hour to the distance covered by the passenger in the train. However, the theory of relativity showed us that these distances cannot be added. This would be just as absurd as multiplying *AB* by *BC* to find the area of the section of a road shown in the figuer on next page, forgetting that the latter is distorted in the figure due to the perspective. Besides, to obtain the passenger's speed relative to the station, we must find the distance travelled



by him in one hour by the station clock, while to arrive at his speed in the train we used the clock in the train, which, as we already know, is not the same by far.

This brings us to the conclusion that velocities, of which at least one is comparable to the velocity of light, are added in a quite different manner from what we are accustomed to. We can observe this paradoxical addition of velocities experimentally when, for example, watching the propagation of light in flowing water (we discussed this earlier). The fact that the velocity of light propagation in





flowing water is smaller than and not equal to the sum of the velocity of light in still water and the velocity of flowing water, is a direct consequence of the theory of relativity.

Velocities are added in a very peculiar manner if one of them is exactly 300,000 km/sec. This velocity, as we know, possesses the property of remaining unchanged, regardless of the motion of the frames from which we observe it. In other words, no matter what velocity is added to 300,000 km/sec we will again get the same 300,000 km/sec.

A simple parallel can be drawn in reference to the inapplicability of the ordinary principle of the addition of velocities.

As you know, in a flat triangle (see left figure on page 53), the sum of angles A, B and C is equal to two right angles. Now let us imagine a triangle drawn on the Earth's surface (see right figure). The sum of the angles of this triangle will be greater than two right angles due to the roundness of the Earth. This difference becomes noticeable only when the size of the triangle is comparable to that of the Earth.

We can use the ordinary rule of velocity addition when dealing with small speeds, just as it is possible to apply the rules of plane geometry to measuring small areas of the Earth's surface.

Chapter Six

MASS

Mass

Suppose we want to make some inertial body move at a definite speed. We shall have to apply a certain force to it. The body will be set in motion and may be accelerated in time to any desired velocity in the absence of external forces such as friction. We will find that different time intervals are required to accelerate different bodies to the desired velocity with the help of a given force.

Disregarding the force of friction, let us imagine two spheres in space identical in size, one made of lead and the other of wood. Let us apply the same force to each of them until they are accelerated to the speed of, say, 10 km/hr.

Evidently, we shall have to apply this force to the lead sphere for a greater length of time than to the wooden sphere: the lead sphere has a greater mass than the wooden one. Since under the action of a constant force, velocity grows proportionately to the time, the mass is the relation of time required to accelerate an inertial body to that velocity. The mass is proportional to this relation, the coefficient being dependent on the accelerating force.

Increasing Mass

Mass is one of the most important properties of any body. We are used to the mass of bodies always being constant It does not depend on velocity. This follows from our initial statement that under the continuous application of a constant force the velocity grows in direct proportion to the time of its application.

This statement is based on the principle of the addition of velocities. However, we have just proved that this principle cannot be applied in all cases.

What are we to do in order to obtain the speed after a force has been applied for, say, two seconds? We conform to the ordinary rule of addition of velocities and add the speed of the body at the end of the first second to the speed it acquired during the next.

We can do so until the velocities approach the speed of light. In that case the old rule becomes inadequate. Adding velocities with due account of the theory of relativity we will get results somewhat smaller than we would if we were to use the old rule of addition, quite useless in this case. This means that a high velocity will increase not proportionally to the time of application of a force but somewhat slower. This is only natural, because there is a limiting velocity.

Given a constant force, the velocity of a body increases slower and slower as it approaches that of light, so that the limiting velocity is never exceeded.

Mass could be considered independent of the velocity of a body as long as we say that the velocity of the body increased proportionally to the time of application of a force. But as soon as the velocity of the body approaches that of light, the proportion between time and velocity disappears and mass becomes dependent on velocity. Since the time of acceleration grows infinitely and velocity cannot be greater than the top limit, we observe that mass grows with velocity, that it becomes infinite when the velocity of the body reaches that of light.

Calculations show that the mass of a moving body increases as much as its length diminishes. Thus, the mass of the Einstein train moving at 240,000 km/sec is $\frac{10}{6}$ times greater than the mass of the same train at rest.

It is quite natural that in dealing with conventional velocities, insignificant compared with the velocity of light, we may disregard the change in mass just as we disregard the connection between the dimension and speed of a body, or the dependence of the time interval between two events on the velocities with which the observers of these events travel.

We can check the relation between mass and velocity, which stems from the theory of relativity, by watching the motion of fast electrons.

In modern experimental devices an electron moving at a velocity close to that of light is quite commonplace. Electrons are accelerated in special machines to speeds only 30 km/sec slower than the speed of light.

It turns out that modern physics is quite capable of comparing the mass of electrons moving at a great speed with the mass of stationary electrons. Experiments have fully confirmed the dependence of mass on velocity, a corollary of the principle of relativity.

What Is the Price of a Gram of Light?

The increment of body mass is closely connected with the work applied to it; it is proportional to the force required to set the body in motion. There is no need to expend work in merely setting the body in motion. All force applied to the body, any increment of body energy, increases its mass. This is exactly why a body has greater mass when heated, why a spring has greater mass when it is compressed. True, the coefficient of proportionality between the change of mass and change of energy is insignificant: to increase the mass of a body by one gram we should have to apply 25,000,000 kWh of energy.

That is why the change in body mass under ordinary conditions is very insignificant and evades the most accurate measurements. Thus, if we heat a ton of water from 0°C up to boiling point, its mass will increase approximately by five-millionths of a gram.

If we burn a ton of coal in a closed furnace, the products of combustion will have a mass $\frac{1}{3,000}$ of a gram less than the original coal and oxygen. This missing mass is carried away by the heat generated in the process of burning.

However, in modern physics we also observe phenomena where the change of mass plays quite a prominent role.

Take the phenomena that occur when atom nuclei collide and new nuclei are formed as a result. When, for example, an atom of lithium collides with an atom of hydrogen, producing two atoms of helium, the mass changes by $\frac{1}{400}$ of its original value.

We have already said that to increase the mass of a body by one gram we must apply as much as 25,000,000 kWh of power. Hence, to convert a gram of lithium and hydrogen into helium 400 times less energy is required:

$$\frac{25,000,000}{400} = 60,000 \text{ kWh!}$$

Now let us try and answer the following question: What substance existing in Nature is the most expensive (if we go by weight)? Radium is considered to be the most expensive. Until recently, one gram of it was said to be worth about a quarter of a million rubles.

But what about the cost of light.

In an electric bulb we get a return of just one-twentieth of spent energy in the form of light. Therefore, a gram of light is equivalent to 20 times as much work as 25,000,000 kWh, i.e., 500,000,000 kWh. That will add up to as much as 5,000,000 roubles if we assume that a kilowatt-hour costs only 1 kopek. It follows that a gram of light costs 20 times as much as a gram of radium.

TO SUM UP

Precise and very convincing experiments force us to admit the validity of the theory of relativity, which reveals most amazing features in the world about us, the features evading us at the first cursory glance.

We have seen the far-reaching and radical changes introduced by the theory of relativity into the basic concepts that man has worked out through centuries of everyday experience.

Does it mean that the physics developed long before the appearance of the theory of relativity is to be thrown overboard like an old and useless shoe?

If this were so, there would be no call to engage in scientific research. Some new theory would be sure to appear and crush the old one.

Imagine a passenger riding in an ordinary express train adjusting his watch because, according to the theory of relativity, it would be behind the clock at the railway station. Everyone would make a laughing-stock of him. The effect of, say, a jolt on a highly precise watch is far greater, not to mention the fact that the difference in question amounts to a microscopic fraction of a second.

The chemical engineer who doubts whether water retains its mass when heated is clearly out of his mind. And, conversely, the physicist dealing with colliding atom nuclei without taking into account the change in their atomic weight in nuclear transformations would be asked to leave the laboratory for being ignorant.

Designers develop—and will continue to develop—their engines in accordance with the old laws of physics, because if they were to introduce corrections based on the theory of relativity, these corrections would have less effect upon their machines than a microbe settling on a flywheel. Physicists experimenting with fast electrons must bear in mind that their mass changes with velocity.

The theory of relativity, far from refuting previous concepts and notions, extends them and defines the boundaries within which these old concepts may be applied without incurring the danger of error. The laws of Nature discovered by physicists prior to the birth of the theory of relativity are not repudiated at all; it is only that their range of application is now more clearly defined.

The relation between the physics based on the theory of relativity, known as relativistic, and the physics of the old school, known as classical, is approximately the same as between higher geodesy, which takes into account the roundness of the Earth, and basic geodesy, which ignores it. Higher geodesy proceeds from the relativity of the vertical, and relativistic physics makes use of the relativity of body dimensions and the time interval between any two events, while classical physics knows nothing of the concept of relativity.

Just as higher geodesy developed from basic geodesy, so relativistic physics grew out of classical physics.

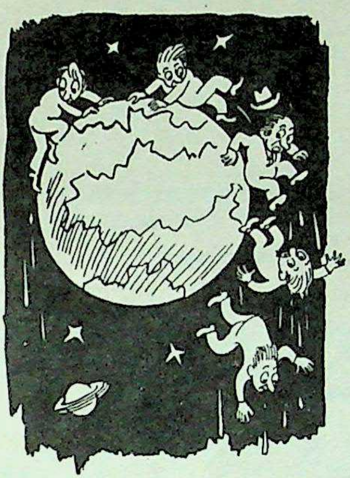
We can change from the formulas of spherical geometry, the geometry of the surface of spheres, to the formulas of plane geometry of the surface of spheres, to the formulas of infinitely long. The Earth will then no longer be a sphere but an infinite plane, the vertical will be absolute, and the sum of the angles in a triangle will be exactly equal to two right angles.

A similar shift may be made in relativistic physics if we assume that the velocity of light is infinitely large, that is, propagation of light is instantaneous.

Indeed, if light propagates instantaneously, the concept of simultaneousness, as we have seen, becomes absolute. The time intervals between events and body dimensions become absolute as well, regardless of the frames from which they are observed.

Consequently, we may retain all the classical concepts if we consider the velocity of light to be infinite.

However, the attempt to combine the limiting velocity of light with the old concepts of space and time puts us in the absurd position of a person who knows that the Earth is round, but insists that the vertical of his native town is an absolute vertical, and does not step outside town limits for fear of tumbling into outer space.



TO THE READER

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I AM A PHYSICIST.

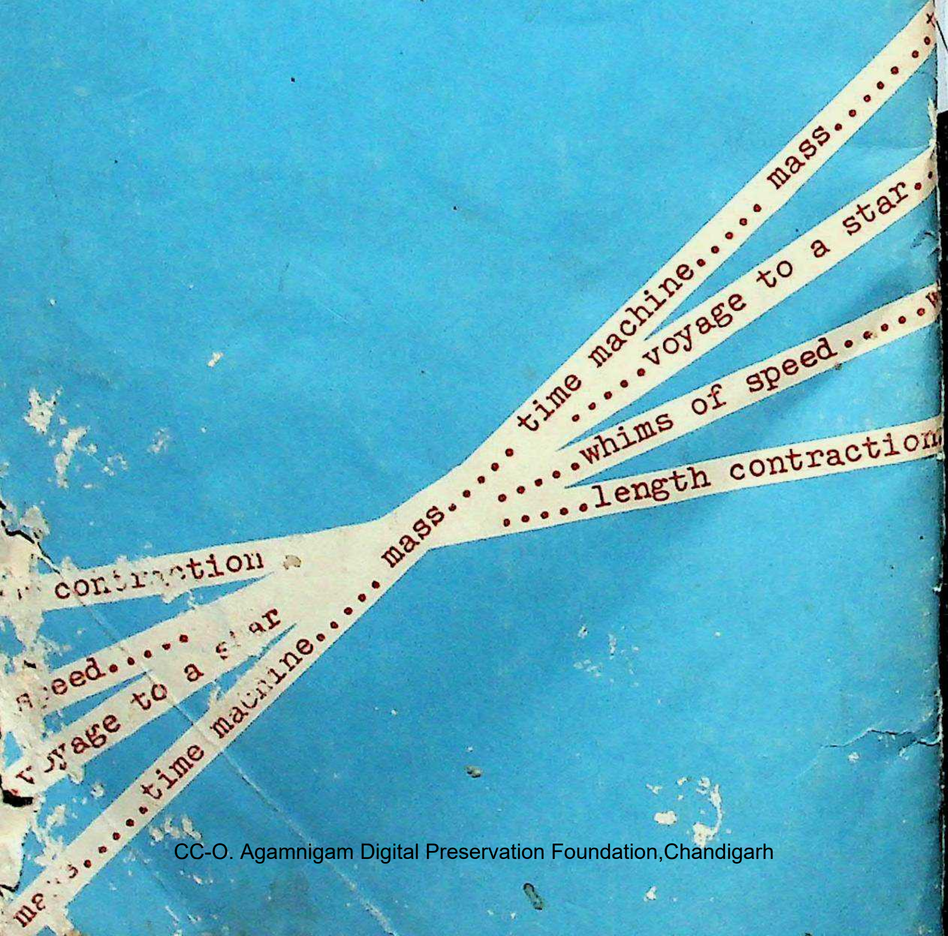
by A. Kitaigorodsky

A great scientist and popularizer of science, co-author with the late Prof. Lev Landau, member of the USSR Academy of Sciences, of 'Physics for Everyone', writes about his favourite science. Why do we need physicists? How is it that physics is penetrating into every field of science today? The author conveys the pleasure physicists get from their work, counsels the reader, and argues with him. His book is intended for everyone, but fellow-physicists will find something of special interest in it.

PHYSICS AND MUSIC

by G. Anfilov

From the primitive reed pipe to modern music "written" by computers is quite a journey. Here, in informal text and about a score of plates, is a story that takes the reader on this interesting trip. *Physics and Music* is also a source of information about the music research that has been underway in the Soviet Union, especially in the scientific manufacture of the violin, and in electrophonic and synthetic music.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.....length contraction
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